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Assessing rugby place kick performance from initial ball flight kinematics: development, validation and application of a new measure

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Abstract

The appropriate determination of performance outcome is critical when appraising a performer's technique. Previous studies of rugby place kicking technique have typically assessed performance based on ball velocity, but this is not the sole requirement. Therefore, a mathematical model of rugby place kick ball flight was developed to yield a single measure more representative of true performance. The model, which requires only initial ball flight kinematics, was calibrated and validated using empirical place kick data, and found to predict ball position with a mean error of 4.0% after 22 m of ball flight. The model was then applied to the performances of 33 place kickers. The predicted maximum distance, a single performance measure which accounted for initial ball velocity magnitude and direction, and spin, was determined using the model and was compared against ball velocity magnitude. A moderate association in the rank-order of the kicks between these two measures (ρ = 0.52) revealed that the relative success of the kicks would be assessed differently with each measure. The developed model provides a representative measure of place kick performance that is understandable for coaches, and can be used to predict changes in performance outcome under different ball launch or environmental conditions.

Keywords

aerodynamics, biomechanics, kicking, model, simulation

Word count: 4869

Introduction

Place kicks contributed 45% of the points scored in a large sample of international Rugby Union matches from 2002-2011 (Quarrie & Hopkins, 2015) and this contribution may increase in games between more closely-matched teams or games of high importance (e.g. 70% of total points in Rugby World Cup finals from 1987-2015 came from place kicks). The average place kicking success percentage in the 582 matches analysed by Quarrie and Hopkins (2015) was 72% (4874/6769 kicks), and if the success percentage of the competing teams' kicks had been reversed in these matches, 14% of the results would have reversed (Quarrie & Hopkins, 2015). Although other factors must be considered, place kick performance is clearly important in determining match outcome and therefore improving place kicking performance provides an important means for enhancing team success.

Given the crucial role of place kicking, it is important for sport biomechanists to understand how successful kicks are achieved. Previous biomechanical studies have analysed kicking leg kinematics during the downswing (Sinclair et al., 2014; Sinclair et al., 2017; Zhang, Liu & Xie, 2012), variability in kicking foot movement at ball contact (Ford & Sayers, 2015), approach to the ball and support foot placement (Baktash, Hy, Muir, Walton & Zhang, 2009; Ball, Talbert & Taylor, 2013; Green, Kerr, Olivier, Dafkin & McKinon, 2016; Cockcroft & van den Heever, 2015), whole-body orientation at ball contact (Ball et al., 2013; Green, Kerr, Olivier, Dafkin & McKinon, 2016) or motion of the non-kicking-side arm (Bezodis, Trewartha, Wilson & Irwin, 2007), and have often attempted to relate these aspects of technique to performance outcome. The majority of these studies were laboratory-based, meaning the full flight path of the ball could not be tracked. Instead, performance was quantified as the initial ball velocity magnitude. However, a sufficiently high ball velocity magnitude is not the complete performance requirement as the ball must pass between two posts (5.6 m apart) and above a crossbar (3.0 m above the ground). Whilst the lateral position of the ball relative to the target line has also been used as an additional performance measure (Bezodis et al., 2007; Green et al., 2016), a single value incorporating the distance and accuracy requirements in to a representative measure of how far any given kick could be taken from and be successful is needed if place kicking performance is to be appropriately assessed in laboratory studies. Importantly, this could lead to a different interpretation of place kick performance outcomes, and thus of the techniques associated with high levels of performance, compared with when the more traditional measure of ball velocity magnitude is used.

Predicting the flight path of the ball from the initial flight kinematics would enable a more complete and meaningful measure to be determined for use in applied research (e.g. how far from the posts any given kick would be successful). The flight path is directly determined by the magnitude and direction of the ball's linear and angular velocities at the instant it leaves the kicker’s boot, and the gravitational and aerodynamic forces which act on the ball during flight. Although the aerodynamic forces cannot be directly measured in flight, wind-tunnel experiments have been conducted to determine the drag, lift, and side forces in simulated rugby ball flight (e.g. Seo, Kobayashi & Murakami, 2006; Seo, Kobayashi & Murakami, 2007). These experiments were conducted with the ball rotating about different principal axes and yielded aerodynamic force coefficients as functions of wind-speed and ball orientation. Whilst these published coefficients can be applied to simulate ball flight, there has been no experimental validation of their accuracy. Furthermore, as there are different functions available, a systematic assessment is required to determine the most appropriate combination of coefficients which best predict the outcome of a kick, and to quantify the accuracy of this prediction. The model can then be applied with confidence to assess performance outcome and also used to provide valuable insight regarding place kick performance, as kicks can be unsuccessful for different reasons. For example, an investigation into how the magnitude and direction of the linear and angular ball velocities differ between sub-groups of kicks which result in different outcomes (e.g. long 'successful' kicks versus those which are less successful because they miss short, left, or right) will provide an understanding of the aspects of ball launch which future technical investigations should endeavour to address.

Our primary aim was therefore to develop and validate a model of ball flight to assess rugby place kick performance using a single measure. This measure should be fully representative of field-based performance and easily understandable for coaches and players. In order to demonstrate the applicability of this measure, we secondly aimed to categorise the performance outcomes of a group of kicks and investigate differences in initial ball flight kinematics between sub-groups. We hypothesised that (1) assessing performance using a single measure based on the modelled flight path would provide a different interpretation of performance levels compared with initial linear ball velocity magnitude, and that (2) both linear and angular (i.e. spin) initial ball flight kinematics would differ between sub-groups of place kicks which result in different outcomes.

Methods

Overview of methodological approach

A mathematical model that simulated the entire flight path of a rugby ball from initial flight kinematics was developed. The combination of aerodynamic force and moment coefficients included in the equations of motion were then selected based on comparison against empirical data from four kickers. The accuracy of the model output was validated against additional empirical data from these kickers. Finally, the validated model was applied to the place kicks of 33 experienced kickers to demonstrate its application and to address our hypotheses. All procedures were approved by the St Mary's University Ethics Committee, and all kickers were free from injury, volunteered, and provided written informed consent.

Model development

A six degree-of-freedom ball flight model was developed in Matlab (v.7.12.0, The MathWorks Ltd., USA). The global coordinate system was aligned such that the y-axis represented the horizontal direction from the kicking tee to the centre of the target, the z-axis was vertical, and the x-axis was the cross-product of the two. The required model inputs were empirically measured initial three-dimensional linear velocity of the ball centre of mass (CM), pitch angle, yaw angle, and the pitch, yaw, and roll velocities of the ball at the onset of flight. The initial roll angle was excluded as it has a negligible effect on the forces subsequently acting (Seo et al., 2004). The ball CM position at the onset of flight relative to its original position on the tee was also input. In order to ultimately determine ball position in all subsequent time iterations (i, 0.0001 s), the side (F_x), drag (F_y) and lift (F_z) forces were first calculated using the following equations (Seo et al., 2006, 2007):

$$F_{x_{(i)}} = C_{x_{(i)}} \cdot \rho \cdot V^{2/3} \cdot 0.5 \cdot \vec{v}_{(i-1)}^{2} \quad (1)$$

$$F_{y_{(i)}} = C_{y_{(i)}} \cdot \rho \cdot V^{2/3} \cdot 0.5 \cdot \vec{v}_{(i-1)}^{2} \quad (2)$$

$$F_{z_{(i)}} = C_{z_{(i)}} \cdot \rho \cdot V^{2/3} \cdot 0.5 \cdot \vec{v}_{(i-1)}^{2} \quad (3)$$

where V = ball volume (0.0048 m^3; Seo et al., 2006), ρ = air density (1.225 kg/m^3 based on the assumption of standard atmospheric conditions at the testing location: 15°C, and 9 m above sea level), and $\vec{v}$ = resultant ball velocity. The three aerodynamic force coefficients (C_x, C_y, C_z) were functions of instantaneous pitch angle (θ_x), yaw angle (θ_y), roll velocity (ω_z) and a spin coefficient (see *Model calibration and validation* section). For some model implementations, the pitch (M_x) and yaw (M_y) moments were required, and were calculated using the following equations (Seo et al., 2006, 2007):

$$M_{x_{(i)}} = Cm_{x_{(i)}} \cdot \rho \cdot V \cdot 0.5 \cdot \vec{v}^{\,2}_{(i-1)} \tag{4}$$

$$M_{y_{(i)}} = Cm_{y_{(i)}} \cdot \rho \cdot V \cdot 0.5 \cdot \vec{v}^{\,2}_{(i-1)} \tag{5}$$

The pitch and yaw moment coefficients (Cm_x and Cm_y, respectively) were represented as functions of instantaneous pitch angle, yaw angle and a spin coefficient. The force and moment coefficients were obtained from previous wind-tunnel experiments (Seo et al., 2006, 2007), and the optimum combination of these coefficients was determined (see *Model calibration and validation* section).

The ball CM linear accelerations (a_x, a_y, a_z) were determined based on the ball's mass (m; 0.435 kg) and gravity (g; 9.81 m/s^2). In versions of the model where moments were included, the angular accelerations (α_x, α_y) were also determined at each time interval accounting for the ball's moment of inertia about the transverse axis (0.0033 $kg.m^2$; Seo et al., 2006). All accelerations were numerically integrated (trapezium rule) to update the linear (v_x, v_y, v_z) and angular (ω_x, ω_y) velocities of the ball, which in turn were numerically integrated to update its position (d_x, d_y, d_z) and orientation (θ_x, θ_y). The model was terminated when one of the following conditions was met:

a) d_x reached ± 2.65 m (the maximum medio-lateral displacement of the ball before it would hit one of the goalposts, assuming it was kicked from directly in front of the posts, accounting for ball size (i.e. 0.30 m long axis) in a horizontal orientation)

b) d_z dropped back below 3.15 m (the height of the crossbar accounting for ball size in a vertical orientation)

The primary output of the model was d_y in the penultimate simulation frame. Assuming that the kick was taken from directly in front of the posts, this value quantified the maximum anterior displacement immediately before the ball would have struck either post or the crossbar. This *predicted maximum distance* measure provided a single objective performance measure of kick length that fully accounted for the initial 3D linear and angular velocities imparted on the ball and the forces experienced during flight. Importantly, this measure is meaningful for coaches and players who commonly refer to kick distances and are fully cognisant of their maximum range. The reason for kick failure (i.e. missing left, missing right or dropping short) was also identified from the model output.

Model calibration and validation

Thirty-eight place kicks were performed by four proficient rugby place kickers (mean ± SD age: 28 ± 4 years, mass: 79.3 ± 6.5 kg, height: 1.81 ± 0.09 m) in an indoor sports hall. All kicks were from a tee positioned 22.00 m from a vertical wall on which a 9.06 × 4.61 m calibrated area was measured. Two synchronised high-speed cameras (Phantom V5.2, Vision Research Inc., USA; 240 Hz, shutter = 1/1000 s) recorded the initial 2.5 m of ball flight. The raw video files were imported into Vicon Motus (v.9, Vicon Motion Systems, UK) and the top and bottom of the ball, the centre of the visible panels (marked on the ball) or the middle of a seam connecting the panels (also marked) were manually digitised at full resolution (1280 × 800 pixels) from 10 frames before initial ball contact until four frames after the ball had visibly left the boot. Due to the potential effects of error in the initial ball flight kinematics on the predicted final ball location, each video clip was digitised 17 times to provide stable values within a bandwidth of ± 0.25 standard deviations either side of the mean, which were considered to be an accurate representation of the true value (Taylor, Lee, Landeo, O'Meara & Millett, 2015).

The 3D trajectories were reconstructed using direct linear transformation (DLT; Abdel-Aziz & Karara, 1971) and exported to Visual3D (v.5, C-Motion, Ltd., USA) to reconstruct the 3D kinematics of the ball. Initial ball flight was identified as the first frame where the raw antero-posterior ball CM velocity first decreased after ball contact (Shinkai et al., 2009). The initial linear ball CM velocity was calculated from polynomial functions fitted to the first four frames of the raw displacement data following initial ball flight (first order for both horizontal directions, second order for vertical). Three-dimensional ball orientations relative to the global coordinate system were calculated using an XYZ Cardan rotation sequence. The initial ball angular velocities were calculated based on the change in ball orientation between the first and fourth frames of flight.

The true ball position after 22.00 m of anterior displacement was measured using two additional synchronised high-speed cameras (Sony FX1000, UK; 200 Hz, shutter = 1/1000 s). One camera was placed close to the target wall to identify the frame in which the ball contacted the wall. The corresponding frame from the other camera (12.00 m in front of the centre of the target wall) was identified and the vertical and medio-lateral positions of the ball were determined from this image using 2D DLT with lens correction.

For this model calibration and validation, the model terminated automatically after 22.00 m of anterior displacement. Using the experimentally-measured initial ball flight kinematics as model inputs, the model output (i.e. position where the ball first made contact with the wall) was compared with the experimentally-measured ball positions for each kick and the root mean square difference was calculated. Half of the trials (i.e. 19) were randomly selected for use in the calibration process to identify the optimal combination of aerodynamic force and moment coefficients from previous wind tunnel experiments of a ball spinning about either the longitudinal (Seo et al., 2006) or transverse axis (Seo et al., 2007). Although the ball primarily spins about the transverse axis during a place kick, when longitudinal spin is imparted to the ball, a lateral deviation in the flight path is observed due to the greater side force (Seo et al., 2006). As no data is available for a ball spinning about multiple axes, the calibration process assessed the accuracy of the model predictions using each of eight different sets of coefficients (Table 1), obtained from both Seo et al. (2006) and Seo et al. (2007). The remaining 19 trials were then used for an independent validation of the model accuracy using the identified optimal coefficient set.

****Table 1 near here****

Model application

In a separate empirical data collection, ball flight data were obtained from 33 competitive rugby kickers (ranging from amateur to senior international, mean ± SD age: 22 ± 4 years, mass: 86.2 ± 8.8 kg, height: 1.82 ± 0.06 m). Each kicker wore moulded boots and performed rugby place kicks in an indoor laboratory with rubber flooring. A 1.2 m wide by 2.3 m high net (The Net Return LLC, USA) was centred 2.00 m in front of the kicking tee. A 0.05 m wide by 1.20 m high target was hung from the top centre of the net to represent the line of the centre of the posts. Six circles of reflective tape (25 mm in diameter) were attached to a size 5 Gilbert Virtuo Matchball, one in the centre of each of the panels of the ball and two at known locations at the top of opposing panels to enable 3D tracking. All trials were recorded at 240 Hz using a 10-camera motion capture system (MX-3, Vicon, UK) with the global coordinate system defined as stated previously. Following a self-directed warm-up and familiarisation kicks the kickers were asked to kick towards the target, as if from their maximum range, for a minimum of seven kicks.

Marker trajectories were reconstructed and labelled using Vicon Nexus (v. 1.8.3). Five kicks for each kicker were selected based on marker visibility and the subjective rating of kick quality (provided by the kicker immediately after the kick on a scale of 1-10, with 10 perceived to be perfect), and exported to Visual 3D. The initial linear and angular ball kinematics were calculated as outlined previously, and were input to the validated ball flight model. The *predicted maximum distance* for each of the five place kicks taken by each kicker was output, and the kick with the greatest *predicted maximum distance* for each kicker was used for all subsequent analysis.

To address the first hypothesis, a Spearman's rank-order correlation coefficient (ρ) was calculated between the *predicted maximum distance* and the magnitude of the resultant initial ball velocity (the measure typically used in previous studies) for the 33 kicks. To address the second hypothesis, the kicks were grouped based on their performance outcome. Initially, those kicks with a *predicted maximum distance* greater than 32 m (the average place kick distance in international matches; Quarrie

& Hopkins, 2015) were identified and termed 'long' kicks. The remaining less successful kicks were sub-divided based on the reason for failure: kicks which dropped below crossbar height (short kicks), kicks which hit the left-hand goalpost (wide-left kicks) or which hit the right-hand goalpost (wide-right kicks). Means and standard deviations were calculated for each sub-group’s initial ball flight kinematics. The initial directions of ball flight (in the x-y plane and y-z plane, termed 'lateral direction' and 'launch angle’, respectively) were determined from the initial ball velocities. Effect sizes were calculated (Cohen, 1988) to assess the magnitude of the difference between the subgroups for each variable. The effect sizes were interpreted as: <0.2, trivial; 0.2 to 0.6, small; 0.6 to 1.2, large and >2.0, very large (Hopkins, Marshall, Batterham & Hanin, 2009). Following this, 90% confidence intervals were calculated and magnitude-based inferences were derived (Hopkins, 2007). A threshold of 0.2 was considered to be a practically important effect (Hopkins et al., 2009; Winter, Abt & Nevill, 2014). The likelihood of the true value falling within each classification of positive, trivial and negative was calculated.

Results

Model calibration and validation

The model containing coefficient set 8 (Table 1) provided the closest match with experimental data (Table 2). This combination of coefficients included drag and lift coefficients for a ball spinning predominantly about the transverse axis (Seo et al., 2007) and a side force coefficient for a ball spinning about the longitudinal axis at a velocity greater than 360°/s (Seo et al., 2006) but no moment coefficients. When the model contained coefficient set 8, its outputs matched the experimental data with a mean resultant difference of displacement in the plane of the posts of 0.87 ± 0.42 m (Table 2). When validated against a further 19 independent kicks, the mean resultant difference was 0.88 ± 0.40 m – this error in displacement in the plane of the posts equated to 4.0% of the total anterior displacement (i.e. 22.0 m) during flight.

****Table 2 near here****

Model application

Using the model containing coefficient set 8, a moderate, positive relationship was observed between the rank orders of the 33 place kicks based on the *predicted maximum distance* and the magnitude of the resultant initial ball velocity (ρ = 0.52, 90% CI = 0.27 to 0.71; Figure 1). The 33 kicks were then categorised into distinct groups based on their outcomes. As two of the kicks were within 4.0% (the accuracy of the model as determined during the validation) of the 32 m *predicted maximum distance* threshold, they could not be confidently categorised and were excluded from all further analysis. Eighteen kicks achieved a *predicted maximum distance* > 32 m and were classified in the long group. Thirteen kicks achieved a *predicted maximum distance* < 32 m. These kicks were then sub-divided based on their reason for failure, with four classified in the short group, eight in the wide-left group and one in the wide-right group. As only one kick was classified in the wide-right group, this group was removed. Thirty kicks, classified into three distinct groups, were therefore included in all subsequent analyses.

****Figure 1 near here****

The *predicted maximum distance* of the long kicks was substantially longer than that of both the wide-left (Figure 2a) and short kicks (Figure 2b) but there was no clear difference between the two less successful groups (Figure 2c). Both the long and wide-left kicks had a substantially faster resultant ball velocity compared with the short kicks (Figure 2b and 2c) but there was no clear difference in ball velocity magnitude between the long and wide-left kicks (Figure 2a). The lateral direction of the ball velocity vector was substantially different between all three groups (Figure 2a-c) with the long and short kicks initially directed towards the right-hand-side and the wide-left kicks towards the left-hand-side. The launch angle of the ball velocity vector was substantially greater for the long kicks than the wide-left kicks (Figure 2a), whilst the short kicks had a substantially greater launch angle than both of the other two groups (Figure 2b and 2c). There was no clear difference in pitch velocity between the three groups (Figure 2a-c) but the long and short kicks possessed substantially less roll velocity (longitudinal spin) than the wide-left kicks (Figure 2a and 2c). The mean ± SD values for these variables are in Table S1 (Appendix 1).

****Figure 2 near here****

Discussion and Implications

We developed and validated a model of rugby ball flight which can be applied to assess place kick performance outcome using a single, representative measure. We also demonstrated the applicability of this model by addressing two specific hypotheses using the model-determined place kick performance measures. The model validation revealed it could accurately predict ball location when in the plane of the posts to within 4.0% of the anterior displacement covered during flight. The model was then applied to obtain a measure of *predicted maximum distance* that quantified the maximum distance from which any given kick could be taken (from directly in front of the posts) and remain successful. Comparison of the performance-based ranking of 33 kicks using this *predicted maximum distance* measure against the traditionally adopted linear velocity magnitude measure (Figure 1) supported our first hypothesis as the rank orders of the 33 kicks were only moderately related (ρ = 0.52). When the kicks were then categorised in to sub-groups based on their performance outcomes, our second hypothesis was also supported as clear differences in both linear and angular initial ball flight kinematics were evident between the sub-groups (Figure 2).

When developing any movement simulation, Hicks et al. (2015) proposed that the model should be calibrated to identify appropriate constants that produce an output closest to empirical data. Previous wind-tunnel experiments (Seo et al., 2006; 2007) have rotated a rugby ball about different axes and in different wind speeds to determine the aerodynamic force and moment coefficients, but no published scientific studies have singularly represented the complete characteristics observed during rugby place kick ball flight. The current model calibration therefore enabled the determination of the set of these coefficients which yielded the most accurate prediction of place kick performance – coefficient set 8 (Table 1) yielded an error in predicted ball displacement in the plane of the posts of 0.87 ± 0.42 m after 22 m of anterior flight (Table 2). The inclusion of moment coefficients increased the ball angular velocities to unrealistic values when visually compared with the empirical trials and observation of place kicking in match scenarios (coefficient set 6; Tables 1 and 2), whilst including side force coefficients for ball flights with low roll velocities resulted in excessive lateral ball displacement (coefficient set 7; Tables 1 and 2).

Having identified set 8 as comprising the coefficients which yielded the most accurate prediction of place kick performance, the model incorporating this coefficient set was then validated against additional independent data. The error (0.88 ± 0.40 m) was consistent with that observed during the calibration process – the model was therefore capable of predicting place kick performance with a mean error of 4.0%. This mean error is considerably smaller than that recorded by Tanino and Suito (2009) who simulated rugby kicks (out of hand) with a mean error of 25.8% of the measured anterior displacement of the ball. The greater accuracy in the current study may be due to Tanino and Suito (2009) only considering the spin of the ball about one axis for each kick type (the longitudinal axis for a screw kick, the transverse axis for a high punt kick). As is evident from the current results, and from the sequence of still images presented by Tanino and Suito (2009), the ball typically rotates about multiple axes; inclusion of these degrees of freedom in the initial flight parameters is therefore necessary. The model estimates demonstrated comparable errors in both the lateral and vertical displacements of the ball (mean absolute errors of 0.59 ± 0.47 m and 0.51 ± 0.35 m, respectively; Table 2). This suggests that there was not a specific model input or parameter that was causing greater error in a particular direction. The 4.0% error in the current model is most likely due to the aerodynamic force values being estimates of the true forces experienced in flight, given the accuracy of the input data obtained through repeated digitisations and the ball location when it hit the wall. Whilst the low magnitude of error in the current model supports the overall accuracy of the utilised values from wind-tunnel experiments (Seo et al., 2006; 2007), future experiments could look to apply constrained optimised functions to fit the aerodynamic forces, using information from empirical ball flights, such as those in the current study.

The calibrated and validated model was then applied to predict the maximum distance that the kicks of 33 rugby place kicks could successfully be taken from. Previous research has typically determined the success of a place kick based solely on the ball velocity magnitude (e.g. Baktash et al., 2009; Sinclair et al., 2014; Zhang et al., 2012). Ball velocity magnitude does not account for the accuracy of a kick, and our results demonstrate that the rank order of kicks based on their velocity is only moderately associated with the rank order based on the *predicted maximum distance* (ρ = 0.52; Figure 1) - the different performance measures give a different interpretation of the relative success of a kick. This is an important consideration for researchers and practitioners as it highlights the importance associated with the choice of measure used to assess performance levels, similar to previous findings in other sporting actions such as the sprint start (Bezodis, Trewartha & Salo, 2010). Whilst a high ball velocity can result in a greater *predicted maximum distance*, the ball velocity magnitude only explains 27% of the variance between the two rank orders, supporting our first hypothesis. Other factors such as the direction of the ball velocity vector and the ball spin must account for the remaining variance. This is further illustrated when performance differences between the sub-groups of kicks are considered. Despite no clear difference in ball velocity magnitude between the long and wide-left kicks, the *predicted maximum distance* of the long kicks was substantially greater; this critical real-world difference in performance outcome would be overlooked if solely assessing performance based on ball velocity magnitude. Additionally, there was no clear difference in *predicted maximum distance* between the short and wide-left kicks, but if performance had been determined simply based on ball velocity magnitude, the wide-left kicks would have been considered to be more successful. These findings provide clear examples supporting the need to use a performance measure that represents overall place kick performance, such as the *predicted maximum distance* value developed in this study. The current findings also illustrate the role of factors in addition to the initial ball velocity magnitude; the initial linear velocity direction and the spin imparted on the ball are also important performance-related factors to consider.

Our second hypothesis was also supported as although there was no clear difference in resultant ball velocity magnitude between the long and wide-left kicks, there were differences in other linear and angular initial ball kinematics (Figure 2). The wide-left kicks demonstrated substantially greater roll velocity which, combined with an initial ball velocity vector directed towards the left-hand-side, caused the ball to pass outside the left-hand goalpost from a distance of less than 32 m. These results provide some support to the assertion from coaching literature that a curved ball trajectory may not be desirable (Bezodis & Winter, 2014; Greenwood, 2003; Wilkinson, 2005) and highlights potential limitations of studies that have not considered this ball flight characteristic. In addition to their previously described lower resultant ball velocity, the short kicks also possessed a substantially higher ball launch angle compared with the long kicks. The short kicks' launch angle is higher than the optimum launch angle identified for place kicks (32.3°) by Linthorne and Stokes (2014), suggesting that changes in ball launch angle could be a simple performance factor for coaches to first manipulate with kickers who lack distance. The current model could be used to inform this – for example, if the maximum initial ball velocity of a kicker is known, the model inputs could be systematically adjusted to identify the optimum launch angle for a given kicker. Furthermore, the model could also be used to inform coaches of the effect of specific environments that may be experienced during matches. For example, the model indicates that a kick which was just successful from 22 m at -5°C at sea level, would be successful from 2.96 m further away if the same kick was taken at 20°C at 1810 m (the altitude of Ellis Park in Johannesburg) based on alterations to the air density constant.

Conclusion

A ball flight model was developed which was capable of predicting the maximum distance any given place kick could be successful from given its initial flight kinematics. The model was able to locate position in the plane of the posts to within 4.0% of the anterior displacement during flight. Differences were found in the rank orders of kicks based on their resultant ball velocity magnitude or the newly proposed *predicted maximum distance* measure, because the ball velocity measure does not account for the accuracy requirement of the task which are clearly an important consideration. When the full flight path of the ball cannot be assessed (e.g. in an indoor/laboratory environment), using the current model to predict the maximum distance provides an ecologically valid assessment of true place kick performance, and one which is readily understandable for players and coaches. The model can also be used by players and applied practitioners to predict the effect of changes to the initial ball flight kinematics on performance outcome, as well as to understand how their performance levels vary in the different environmental conditions that they may encounter.

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Appendix 1

Table S1. Initial ball flight kinematics of the three groups (mean ± SD).

	Long Kicks	Wide-left Kicks	Short Kicks
Predicted maximum distance (m)	39.30 ± 4.92	25.88 ± 3.24	27.25 ± 3.80
Resultant velocity (m/s)	27.6 ± 1.7	26.9 ± 1.6	20.8 ± 2.2
Lateral direction (°)	1 ± 3	-1 ± 2*	2 ± 3
Launch angle (°)[†]	31 ± 3	28 ± 7	35 ± 3
Pitch velocity (°/s)	2263 ± 877	2307 ± 663	2070 ± 1377
Roll velocity (°/s)	288 ± 206	746 ± 466	473 ± 394

* A negative lateral direction indicates that the ball was initially travelling towards the left-hand-side of the goalposts, with a positive value directed towards the right-hand-side. [†] The launch angle represents the direction of the ball flight in the y-z plane.

List of tables

Table 1. The sets of aerodynamic coefficients included within the model for the calibration process.

Coefficient set	Side force coefficient (Seo et al., 2007)*	Side force coefficient (Seo et al., 2006)*	Drag force coefficient	Lift force coefficient	Pitching moment coefficient	Yaw moment coefficient
1	-	-	-	-	-	-
2	-	-	✓	✓	-	-
3	✓	-	✓	✓	-	-
4	✓	-	✓	✓	-	✓
5	✓	✓	✓	✓	-	✓
6	✓	✓	✓	✓	✓	✓
7	✓	✓	✓	✓	-	-
8	-	✓	✓	✓	-	-

* When both side force coefficients were included in a model version, the coefficient presented by Seo et al. (2007) was applied to those trials where the roll velocity of the ball was less than or equal to 360°/s, whilst the coefficient presented by Seo et al. (2006) was applied to those trials where the roll velocity of the ball was greater than 360°/s.

Table 2. Absolute differences between the predicted and true ball positions for each coefficient set included in the ball flight model calibration (all data presented as mean ± SD).

Coefficient set	Difference in resultant displacement in the plane of the posts (m)	Difference in lateral position in the plane of the posts (m)	Difference in vertical position in the plane of the posts (m)
1	1.59 ± 0.54	0.95 ± 0.84	1.06 ± 0.35
2	1.18 ± 0.68	0.93 ± 0.75	0.53 ± 0.36
3	1.72 ± 1.06	1.56 ± 1.08	0.58 ± 0.40
4	1.39 ± 0.69	1.15 ± 0.71	0.60 ± 0.40
5	1.06 ± 0.60	0.84 ± 0.58	0.60 ± 0.40
6	0.99 ± 0.50	0.76 ± 0.54	0.53 ± 0.37
7	1.47 ± 1.07	1.29 ± 1.10	0.59 ± 0.39
8*	0.87 ± 0.42	0.59 ± 0.47	0.51 ± 0.35

* Model version 8 was identified as providing the most accurate representation of ball flight and therefore, used for all subsequent analyses.

Figure captions

Figure 1. The performance rankings of the best kicks of 33 kickers based on their *predicted maximum distance* and the magnitude of their resultant initial ball velocity. A ranking of 1 represents the best performance and 33 the worst. The grey dotted line represents a perfect rank order correlation; those kicks below the line were ranked higher based on their resultant velocity and those above the line were ranked higher on their *predicted maximum distance*.

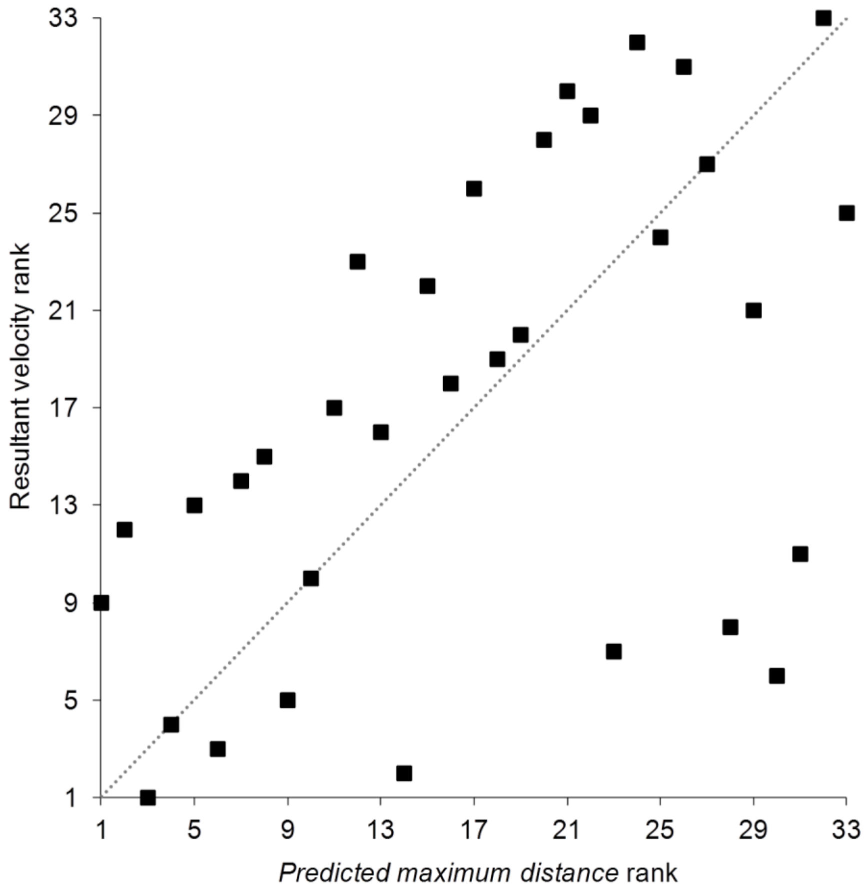

Figure 2. Effect sizes (± 90% CI) between initial ball flight kinematics of a) the long and wide-left kicks, b) the long and short kicks and c) the wide-left and short kicks. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative│trivial│positive. *A negative effect represents a lateral ball velocity vector directed more towards the left-hand-side of the goal whilst a positive effect was more towards the right-hand-side of the goal.